

# The astroclimatological comparison of the Paranal Observatory and El Roque de Los Muchachos Observatory

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## ABSTRACT

The new extremely large telescope projects need accurate evaluation of the candidate sites. In this paper we present the astroclimatological comparison between the Paranal Observatory, located on the coast of the Atacama Desert (Chile), and the Observatorio del Roque de Los Muchachos (ORM), located in La Palma (Canary Islands). We apply a statistical analysis using long term databases from Paranal and Carlsberg Meridian Telescope (CAMC) weather stations. The monthly, seasonal and annual averages of the main synoptical parameters in the two sites are computed. We compare the long term trends in order to understand the main differences between the two sites. Significant differences between the two analyzed sites have been found. Temperature have increasing trends in both observatories with somewhat higher evidence at ORM. Seasonal variations of pressure at Paranal have been highly decreasing since 1989 and we do not see the same phenomenon at ORM. The two sites are dominated by high pressure. In cold seasons  $RH$  is lower than 60% at CAMC and 15% at Paranal. In warm seasons  $RH$  is lower than 40% at CAMC and 20% at Paranal. The analysis of the dew point has shown better conditions at Paranal with respect to CAMC in winter, autumn and spring before 2001, while the two sites are becoming similar afterwards. Winds at ORM are subject to pronounced local variations.

**Key words:** Site testing – Atmospheric effects – Methods: data analysis.

## 1 INTRODUCTION

This study follows a series of papers aimed to compare two of the most important sites candidates to host the future extremely large ground based telescopes. The analysis of the astronomical and meteorological parameters in different sites are conducted, since today, using different approach. In this work we want to apply same methods to compare two different and important sites for the development of the astronomical observations: the site of Paranal Observatory located in the Atacama Desert (Chile, southern hemisphere), and the Observatorio del Roque de Los Muchachos (ORM) located at La Palma (Canary Islands, northern hemisphere). The two opposite locations have different observing characteristics not only because it is possible to see two different sky regions, but also because the oceanic currents impress different climatic regimes to the two sites. While Paranal is located in a desert area, 12 km far from the Pacific Ocean, and it is subjected to the os-

cillating weather variation due the presence of El Niño and La Niña events (Sarazin(**author?**) 1997), the ORM is influenced by a semipermanent Azores high pressure system and it is influenced by the almost periodical variation of the North Atlantic Oscillation (NAO) (Wanner et al. (**author?**) 2001; Graham(**author?**) 2005; Lombardi et al. (**author?**) 2006).

More than 20 years of meteorological data have been collected at ORM using the Carlsberg Automatic Meridian Circle (CAMC) meteorological station and a detailed analysis can be found in Lombardi et al. (2006) (hereafter Paper I) and Lombardi et al. (2007) (hereafter Paper II). Paper I presents a complete analysis of the vertical temperature gradients at Telescopio Nazionale Galileo (TNG) and their correlation with the astronomical seeing. Instead, Paper II reports an analysis of the correlation between wind and astronomical parameters as well as the overall long term weather conditions at ORM. Differences in the ORM microclimate have been demonstrated in a detailed comparison between synoptical parameters taken at three different locations in the observatory on a 1000 m spatial scale. ORM

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**Table 1.** Geographical positions of Paranal and CAMC.

	Latitude	Longitude	Height [m a.s.l.]
Paranal	24° 37' 31" S	70° 24' 10" W	2636 <sup>[a]</sup>
CAMC	28° 45' 36" N	17° 52' 57" W	2326 <sup>[b]</sup>

[a] Platform altitude.

[b] Dome floor.

**Table 2.** Available databases for the observatories. The data coverage with respect to the Total is also reported.

	TNG	CAMC	Paranal
Data rate	30 sec	5 min	20 min
Begin	March 1998	May 1984	January 1985
End	December 2007	March 2005	December 2006
Total	~10 yr	~21 yr	~22 yr
Data coverage			
<i>T</i>	87%	87%	80%
<i>P</i>	87%	86%	71%
<i>RH</i>	85%	85%	80%
<i>T<sub>DP</sub></i>	85%	85%	80%
<i>w<sub>dir</sub></i>	87%	85%	75%
<i>w<sub>sp</sub></i>	87%	86%	80%

shows to be dominated by high pressure, and characterized by an averaged relative humidity lower than 50%. Finally, in Lombardi et al. (2008a) we have analysed in detail the properties of the dust concentration on La Palma from ground based measurements and estimated the aerosol extinction in *B*, *V* and *I* on the site.

Extensive site testing campaigns have been conducted on the top of the Paranal Observatory since years. Thanks to the excellent results, the site was chosen to host the four Very Large Telescopes (VLT) by the European Southern Observatory (ESO).

This site, like La Silla, the other Chilean ESO site, have been very deeply analyzed by ESO teams. Now ESO telescopes are considered the touchstones and their characteristics are used to be compared with the other sites and the other telescopes.

The present paper is organized as follows:

- **Section 2:** describes the Paranal Astronomical Site Monitor and the data reduction;
- **Section 3:** compares the temperature, pressure, relative humidity and correlate each parameter with the Southern Oscillation Index (at Paranal) and NAO (at ORM);
- **Section 4:** shows the dew point comparison at the two sites;
- **Section 5:** analysis of wind direction and wind speed;
- **Section 6:** summarization of the final conclusions.

## 2 DATA REDUCTION

Table 1 that lists positions and heights of the telescopes at observatories. Paranal is almost 300 m higher than CAMC and about 4° closer to the Equator.

Table 2 reports the databases characteristics. The Paranal Astronomical Site Monitor is located in the north area of

the Paranal Observatory platform and hosts several instruments used in the characterization of the site. In particular in this paper we make use of the meteorological data from the Vaisala tower.

The Vaisala tower is a robust steel structure having a total height of 30 m. All the data are regularly collected since January 1st, 1985 and have to be intended as 20 minutes averages. The external air temperature (*T*) is simultaneously measured at 2 and 30 m above the ground (same height of the VLT's domes) with an accuracy of ±0.2°C (Sandrock et al.(author?) 1999). Air pressure (*P*) and relative humidity (*RH*) are measured at 2 m above the ground with an accuracy of ±0.1 hPa and ±1% respectively.

Wind speed (*w<sub>sp</sub>*, in [m s<sup>-1</sup>]) and wind direction measurements are taken at 10 m above the ground with a precision of ±0.5 m s<sup>-1</sup> for the wind speed and ±3° for the wind direction. Following the same statistical procedures of Paper I and Paper II we have computed the hourly averages and then the monthly averages starting from the *T*, *P*, *RH* and *w<sub>sp</sub>* raw data series.

A particular care is used to minimize any effect due to biases in case of lacking of data that typically occurred in winter time. For each missing month value we take into account the average obtained from the two corresponding months in other years in which the values of the months before and after the absent one are similar. For example, if the lacking month is September 2002, we look for the two Augests and Octobers in the other years having similar mean values of August and October 2002. The accepted September 2002 value is the average of the Septembers corresponding to the chosen Augests and Octobers. This is the main reason why we decided to use monthly averages as an intermediate step in the calculation of the annual averages. Finally, we compute the annual averages of *T* from the monthly ones for the three telescopes (see Paper I).

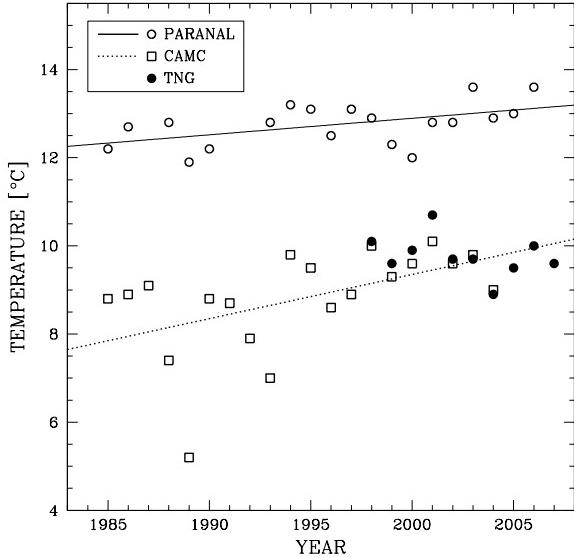
We provide to report in tables the annual values and the rms of the annual averages of the most important meteo parameters.

Wind direction statistics is evaluated by calculating the annual percentage of hours in which the wind comes from each direction  $\vec{D}$ . The wind rose has been divided into 8 mean directions (N, NE, E, SE, S, SW, W, NW) and the percentages of hours are calculated into intervals defined as [ $\vec{D} - 22.5^\circ$ ,  $\vec{D} + 22.5^\circ$ ].

CAMC data from Paper I and Paper II are used in order to compare ORM with Paranal. For what concerns the temperature trend at ORM we decided to take into account also data recorded at TNG because they extent to year 2007 (3 years more than CAMC). Telescopes at ORM are located on a space baseline of about 1000 m (see Paper I).

The TNG meteo tower is a robust steel structure with a total height of 15 m. The tower is located about 100 m far from TNG building. The data are regularly sent from the tower to TNG annex building by means of an optic fiber link since 27 March 1998. The data sampling rate is 10 seconds, while data storage is done every 30 seconds.

The CAMC carried out regular meteorological observations in the period 13 May 1984 to 31 March 2005 and the records are more or less continuous in that period. For the years 1984, 1985 and 1986 meteorological readings are only available at 30 minute intervals. From January 1987 readings were made at 5 minute intervals throughout the day and



**Figure 1.** Annual temperatures at Paranal (circles), CAMC (squares) and TNG (filled circles). The solid and the dotted lines indicate the linear fit of the data for Paranal and CAMC respectively.

night regardless of whether observing was in progress. Beginning in December 1994, all readings were made at 20 seconds intervals and then averaged over 5 minutes<sup>1</sup>. Both Paranal and ORM are located well above the inversion layer, in fact the altitude of the inversion layer at Paranal is about 1000 m as reported by Sarazin (1994), while at ORM it occurs in the range between 800 m and 1200 m (McInnes & Walker(**author?**) 1974).

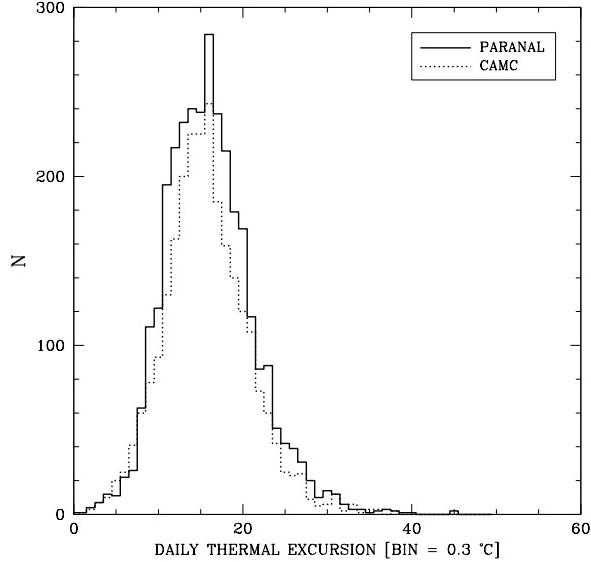
### 3 ANALYSIS OF $T$ , $P$ , SOI AND RH

#### 3.1 Temperature

Table 3 reports the computed mean annual temperatures for Paranal, CAMC and TNG. Values in parenthesis correspond to the rms of the annual averages.

The Paranal temperature is taken at two different levels, at 2 and 30 m above the ground ( $T_2$  and  $T_{30}$  respectively). The vertical variation of temperature with the altitude (wet and dry adiabatic lapse rate) is between 6.0 and 10.0°C/km (Kittel & Kroemer(**author?**) 1980), so we expect a  $\sim 0.2\text{--}0.3^\circ\text{C}$  difference in temperature between the two sensors at 2 and 30 m. As shown in Table 3, the mean difference of the temperature taken at the two heights is 0.2°C, that is comparable with the accuracy of the sensor. For this reason we decide to use the 22 years long database at 2 m as representative of the temperature at Paranal. For completeness, Table 3 reports also the annual  $T$  of CAMC measured at 10.5 m above ground and TNG measured at 10.0 m above ground (see Paper I).

Figure 1 shows the plot of the  $T_2$  annual mean values re-



**Figure 2.** Thermal excursion distribution at Paranal (solid line) and CAMC (dotted line) after 1998. The two sites are almost equivalent.

ported in Table 3 as well as the annual temperature measured at CAMC and TNG. The data show an offset of about 4°C between Paranal and ORM. Furthermore the rms of the annual averages are about 3 times higher at ORM with respect to Paranal. This suggests an higher temperature variations during the years at ORM. Trends at Paranal and CAMC show a positive slope during the years, while TNG data have a flat trend. The best linear fit of CAMC data gives an increase of the temperatures of about  $(1.0 \pm 0.3)^\circ\text{C}/10\text{yrs}$ , while the slope computed for Paranal gives a value of  $(0.4 \pm 0.1)^\circ\text{C}/10\text{yrs}$ . This is not surprising considering that the global warming and the glacier retreat are less pronounced in South America. To facilitate the comparison, it is also drawn the total average for Paranal and CAMC.

But it is interesting to note that after 1998 data at TNG seem to indicate a flattening of the increasing temperature trend. This rises the question if we are in presence of a global warming or it is a typical temperature oscillation through decades and/or a regional effect.

The 22 years long baseline of Paranal is characterized by an increasing trend, the linear regression of Paranal data in the period 1993–2000 shows a slope of  $(-0.12 \pm 0.05)$  while data in the period 2000–2006 have an opposite slope slightly steeper  $(0.19 \pm 0.07)$ . This suggests a possible correlation with the occurrence of wide-scale climatological events such as El Niño and La Niña phenomena. In fact, a preliminary check has shown the presence of strong La Niña episodes in 1999 and 2000 that are linked to the coldest annual temperatures at Paranal (see Section 3.4).

This confirms the strong link between air and ocean temperature that may influences the high level of the atmosphere. The year 1989 appears to be the coldest for both sites in the last 20 years. The year 2001 is the warmest for CAMC while the 2003 and 2006 are the warmest for Paranal.

The typical 3–4 years oscillation of the temperatures at

<sup>1</sup> <http://www.ast.cam.ac.uk>

**Table 3.** Mean annual temperatures at Paranal, CAMC and TNG [°C]. Values in parenthesis correspond to the rms of the annual averages.

Year	1985	1986	1987	1988	1989	1990	1991	1992
Paranal $T_2$	12.2(1.4)	12.7(1.1)	—	12.8(2.0)	11.9(1.6)	12.2(1.7)	—	—
Paranal $T_{30}$	—	—	—	—	—	—	—	—
CAMC $T_{10}$	8.8(4.4)	8.9(3.9)	9.1(3.1)	7.4(5.4)	5.2(4.3)	8.8(5.1)	8.7(4.8)	7.9(4.2)
TNG $T_{10}$	—	—	—	—	—	—	—	—
Year	1993	1994	1995	1996	1997	1998	1999	2000
Paranal $T_2$	12.8(1.4)	13.2(1.3)	13.1(1.3)	12.5(1.2)	13.1(1.6)	12.9(2.1)	12.3(1.4)	12.0(1.7)
Paranal $T_{30}$	—	—	—	—	—	—	—	11.9(1.7)
CAMC $T_{10}$	7.0(5.2)	9.8(4.9)	9.5(4.3)	8.6(5.1)	8.9(4.0)	10.0(5.0)	9.3(5.2)	9.6(5.1)
TNG $T_{10}$	—	—	—	—	10.1(5.1)	9.6(5.3)	9.9(5.3)	—
Year	2001	2002	2003	2004	2005	2006	2007	Average
Paranal $T_2$	12.8(1.3)	12.8(1.6)	13.6(1.3)	12.9(1.5)	13.0(1.3)	13.6(0.8)	—	12.8 ± 0.5
Paranal $T_{30}$	12.6(1.3)	12.6(1.7)	13.5(1.3)	12.7(1.4)	12.6(1.4)	13.3(0.9)	—	—
CAMC $T_{10}$	10.1(4.3)	9.6(4.3)	9.8(4.8)	9.0(4.9)	—	—	—	8.8 ± 1.2
TNG $T_{10}$	10.7(4.1)	9.7(4.5)	9.7(4.8)	8.9(5.0)	9.5(4.1)	10.0(4.7)	9.6(5.1)	—

**Table 4.** Mean annual air pressure at Paranal and CAMC [hPa]. Values in parenthesis correspond to the rms of the annual averages.

Year	1985	1986	1987	1988	1989	1990
Paranal	—	—	—	—	743.3(1.2)	743.3(0.9)
CAMC	774.3(2.6)	775.5(2.3)	774.1(1.8)	773.8(2.2)	773.6(2.3)	774.2(2.4)
Year	1991	1992	1993	1994	1995	1996
Paranal	—	—	743.1(0.7)	743.5(0.5)	743.7(0.7)	743.3(0.6)
CAMC	774.4(2.5)	774.5(2.2)	773.9(2.7)	775.1(1.8)	774.6(2.2)	775.5(3.8)
Year	1997	1998	1999	2000	2001	2002
Paranal	743.3(0.7)	743.5(0.5)	743.5(0.4)	743.2(0.6)	743.4(0.4)	743.5(0.3)
CAMC	775.4(2.4)	775.9(2.2)	775.4(2.2)	775.4(2.4)	776.2(2.5)	776.1(2.4)
Year	2003	2004	2005	2006	Average	
Paranal	743.0(0.4)	743.6(0.4)	743.8(0.4)	743.8(0.4)	743.5 ± 0.2	
CAMC	776.1(2.4)	776.0(2.7)	—	—	775.0 ± 1.0	

CAMC pointed in Paper I is not so clear for Paranal. An interesting results comes from the analysis of the daily thermal excursion after 1998 in the two sites, in fact looking at Figure 2 we do see a very similar distribution for both sites with a peak at bin number 18, corresponding to a thermal excursion of about 4.8°C.

### 3.2 Air pressure

Figure 3 shows the annual mean pressure  $P$  calculated at Paranal and CAMC. Table 4 reports the values plotted in the figure. The average pressure at Paranal during the entire baseline is 743.5 hPa, while the average pressure at CAMC is 775.0 hPa. The plot shows two different behaviors at Paranal with a changing of slope in the year 2000. Splitting the fit in two subsamples we see that the best fit of the points before the 2000 is almost flat ( $\pm 0.1$  hPa) with a mean value of 743.4 hPa. The best fit after the year 2000 is characterized by a positive slope of about ( $0.1 \pm 0.1$ ) hPa and the mean pressure is 743.5 hPa. This difference is comparable to the accuracy of the measuring instruments. A more detailed analysis is needed to check if this is a long term increasing trend of pressure. The data obtained from CAMC show a similar in-

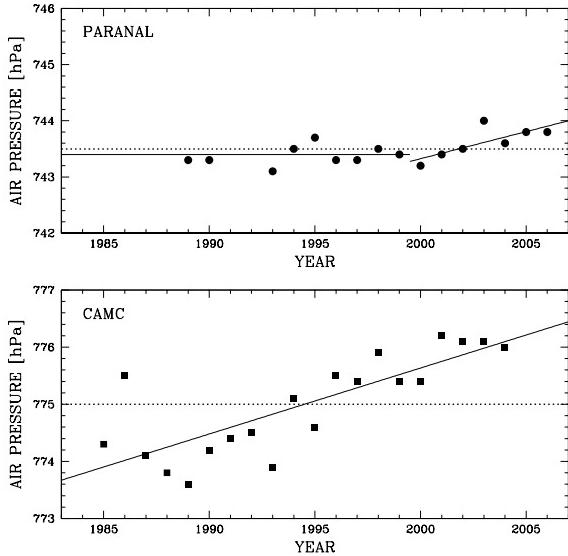
creasing trend during the years ( $\sim 1.5$  hPa, see Paper II). The minimum pressure measured at Paranal was 728.0 hPa in September 1989, while the highest one was in April 1998 with a value of 754.0 hPa. Instead, CAMC minimum pressure was 747.7 hPa in September 2004, while the maximum was 785.8 hPa in July 2001.

Two interesting plots are shown in Figures 4 and 5, where the monthly  $P$  averages in the two sites are plotted. There is a clear decreasing of the dispersion of the monthly  $P$  during the years at Paranal (Figure 4, top) as confirmed by the analysis of the standard deviation of the annual averages (Figure 4, bottom). In fact at Paranal it decreased of about 70% between 1990 and 2006, while the same data computed at CAMC do not show the same phenomenon (Figure 5). The same analysis applied to monthly temperatures shows a lower seasonal dispersion at Paranal ( $\sim 8^\circ\text{C}$ ) with respect to CAMC ( $\sim 19^\circ\text{C}$ ). Temperature dispersion remained almost constant up to now in both sites.

To check if the effect of the yearly variation of the pressure at Paranal can be explained taking into account wide-scale climatological episodes, we have checked a possible correlation with the Souther Oscillation Index. This analysis will be discussed in Section 3.4.

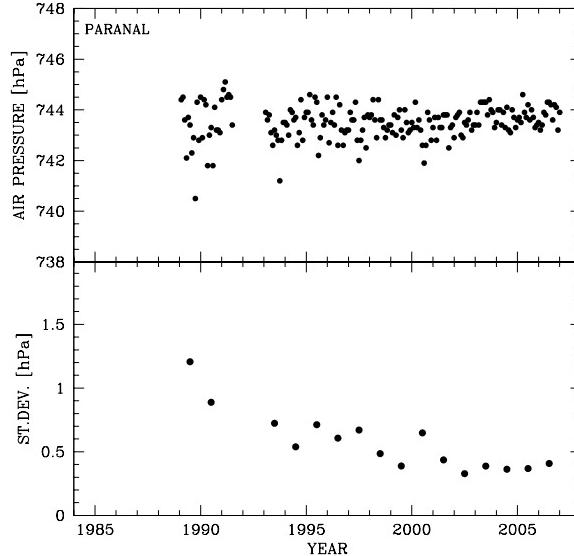
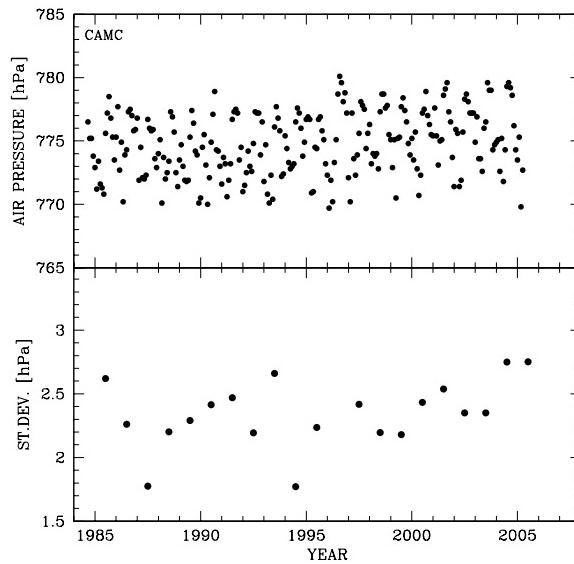
**Table 5.** Seasons definition at Paranal and CAMC.

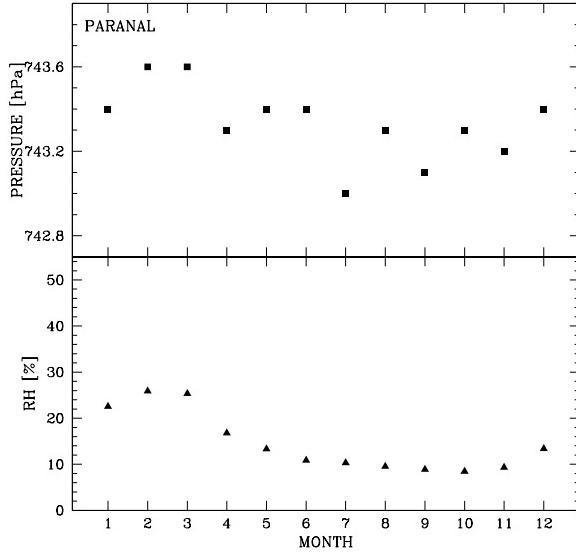
	Paranal	CAMC
WINTER	July-August-September	January-February-March
SPRING	October-November-December	April-May-June
SUMMER	January-February-March	July-August-September
AUTUMN	April-May-June	October-November-December

**Figure 3.** Top: annual  $P$  at Paranal Observatory. Bottom: annual  $P$  at CAMC. The averages are represented by the dotted lines, while the linear fits by the solid lines.

Following Paper II, we have calculated the theoretical pressure for Paranal using the barometric correction that depends on sites scale height  $H$  in the barometric law. The knowledge of the average pressure and the atmospheric scale height are important parameters to compute the local contribution of the Rayleigh scattering to the total astronomical extinction (Hayes & Latham(**author?**) 1975).

At CAMC we have found a typical scale height  $H_{CAMC} = 8325$  m and a theoretical pressure of 766.0 hPa in the period between 1998-2004, while the data give 775.9 hPa on average, confirming that ORM is dominated by high pressure (Paper II, Section 5.1). Since the barometric correction is a function of the mean temperature  $\langle T_{layer} \rangle$  of the layer in which the correction is applied, we have taken into account as closest weather station the city of Antofagasta, close to the Pacific Coast, few meters above sea level. Between 1998 and 2004 the mean temperature of Antofagasta was  $16.7 \pm 0.4^\circ\text{C}$ <sup>2</sup>, while the mean temperature computed at Paranal in the same years was  $12.8 \pm 0.5^\circ\text{C}$ . These two mean temperatures (Paranal and Antofagasta) allow us to calculate the mean temperature of the layer between the sea level and the Paranal, using the weighted average of the two measurements. We obtain  $\langle T_{layer} \rangle = 15.2 \pm 0.5^\circ\text{C}$ . The standard atmospheric model from NASA's Glenn Re-

**Figure 4.** Top: Monthly  $P$  at Paranal. Bottom: Standard deviation of the monthly  $P$  at Paranal.**Figure 5.** Top: Monthly  $P$  at CAMC. Bottom: Standard deviation of the monthly  $P$  at CAMC.<sup>2</sup> See <http://www.tutiempo.net>.



**Figure 6.** Averages of monthly  $P$  (top) and  $RH$  (bottom) at Paranal.

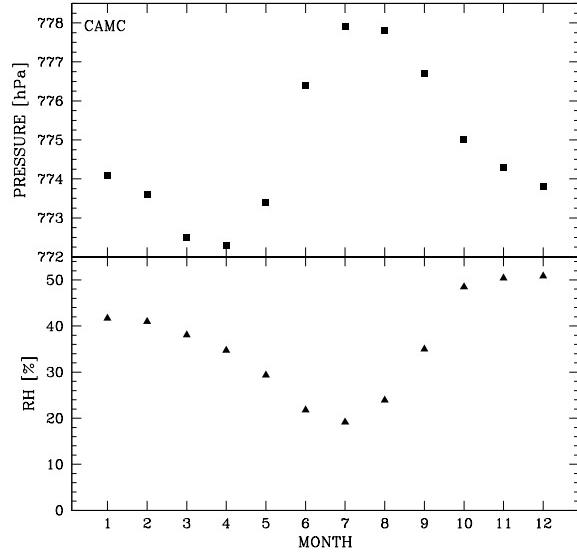
search Center (GRC) Web site<sup>3</sup> permits us to calculate the theoretical pressure at the altitude of Paranal for a  $\langle T_{layer} \rangle = 15.0^{\circ}\text{C}$  which gives a resulting theoretical pressure of 734.4 hPa, and a theoretical scale height  $H_{GRC} \approx 8238$  m. Instead, using standard tables in Allen (2000), for  $\langle T_{layer} \rangle = 15.0^{\circ}\text{C}$ , we find a theoretical scale height  $H_{Allen} \approx 8430$  m, in good agreement with  $H_{GRC}$ . The mean value between  $H_{GRC}$  and  $H_{Allen}$  gives us  $H_{Paranal} = 8334$  m which corresponds to a theoretical pressure for Paranal of  $P_{Paranal} = 738.3$  hPa. This result is lower with respect to the empirical pressures reported in Table 4, so we can confirm that also Paranal is dominated by high pressure. The Paranal scale height is a bit higher than at ORM (8334 m vs 8325 m) as expected having a lower latitude site and higher average temperature than ORM.

### 3.3 Relative humidity

The relative humidity ( $RH$ ) and the dew point are two important parameters for the astronomical instrumentation, because they set the occurrence of moist and water condensation on the coldest part of the telescope and of the instruments. In particular these parameters may affect the upper surface of the main mirror and the pipes of the cooling system.

We separated the annual  $RH$  in 4 seasons as defined in Table 5. Note that Paranal and ORM are in opposite hemispheres, so the definitions are inverted for the two observatories.

To facilitate the discussion we consider as *cold season* autumn and winter, and *warm season* spring and summer. Tables 6 and 7 report the computed annual  $RH$  in cold and warm seasons at Paranal and CAMC. Typically in cold seasons  $RH$  is lower than 60% at CAMC and 15% at Paranal. In warm seasons  $RH$  is lower than 40% at CAMC and 20%



**Figure 7.** Averages of monthly  $P$  (top) and  $RH$  (bottom) at CAMC.

at Paranal. Figures 6 and 7 show the seasonal trend of  $P$  (top) and  $RH$  (bottom) in both sites considered as the average of the same month through the considered years of the databases. The variation of  $P$  at Paranal is  $< 1$  hPa, very lower with respect to CAMC ( $\sim 6$  hPa). Variations of pressure in a short time scale (few hours) can induce weather instabilities, while in a long time scale they increase the differences in the weather in different seasons.

We clearly see an anti-correlation between  $P$  and  $RH$  in summer at CAMC, while at Paranal this effect is not obvious. Because of the effect of the Bolivian Winter, driving equatorial humid air from Amazonian basin along the Andes, the  $RH$  at Paranal is higher in warm seasons ( $\sim 20\%$ ) with respect to cold ones ( $\sim 12\%$ ). Higher  $RH$  appears clearly in wintertime than in summertime at CAMC.

A standard requirement for the use of telescopes is a  $RH$  value  $< 80\%$  or  $< 85\%$ . For both sites we have calculated the number of nights in which  $RH$  has been higher than the mentioned limits for more than 50% of the duration of the night. Only nights which duration has been  $\geq 6$  hours have been used in the calculation. Results are reported in Table 8 and denote a significant difference between Paranal and CAMC, the first appearing almost immune to high  $RH$  events. The number of nights at CAMC is the same for the two imposed limits.

### 3.4 The Southern Oscillation Index (SOI)

In Paper I we demonstrated the correlation between the North Atlantic Oscillation Index and the annual mean temperatures at CAMC (c.l.  $\sim 0.9$ ). The NAO is the dominant mode of atmospheric circulation in the North Atlantic region and is generally defined as the difference in pressure between the Azores high pressure and the Icelandic low pressure (Wanner et al.(author?) 2001; Graham(author?) 2005; Paper I Section 4). We pointed that the action of a positive NAO Index is as a brake for the increase in tem-

<sup>3</sup> See <http://www.grc.nasa.gov>.

**Table 6.** Mean annual *RH* in cold seasons at Paranal and CAMC [%]. Values in parenthesis correspond to the rms of the annual averages.

Year	1985	1986	1987	1988	1989	1990	1991	1992
Paranal	9.1(2.4)	9.7(4.6)	—	9.2(5.1)	12.0(5.5)	9.6(2.1)	—	—
CAMC	40.3(7.0)	43.8(4.1)	48.2(2.5)	52.2(7.0)	49.2(3.6)	56.5(14.7)	57.4(10.2)	52.7(4.7)
Year	1993	1994	1995	1996	1997	1998	1999	2000
Paranal	10.8(3.8)	11.0(4.2)	10.5(3.1)	10.7(3.0)	14.8(3.9)	12.6(4.3)	10.9(2.0)	14.9(4.7)
CAMC	47.8(9.3)	40.4(8.8)	40.6(8.6)	53.1(12.7)	44.7(12.4)	30.9(6.1)	12.5(7.7)	53.0(13.6)
Year	2001	2002	2003	2004	2005	2006	Average	
Paranal	12.5(4.3)	14.5(6.3)	11.4(3.0)	12.4(3.0)	11.5(1.3)	12.4(3.6)	11.6 ± 1.8	
CAMC	33.7(14.7)	56.4(8.9)	36.3(10.8)	40.8(12.8)	—	—	44.5 ± 10.1	

**Table 7.** Mean annual *RH* in warm seasons at Paranal and CAMC [%]. Values in parenthesis correspond to the rms of the annual averages.

Year	1985	1986	1987	1988	1989	1990	1991	1992
Paranal	—	16.9(8.3)	15.8(7.0)	13.0(4.6)	16.9(12.9)	11.5(4.4)	16.3(6.8)	—
CAMC	43.1(3.5)	42.0(7.3)	43.6(4.6)	30.8(7.8)	35.9(10.1)	42.5(14.3)	29.2(10.3)	26.1(12.0)
Year	1993	1994	1995	1996	1997	1998	1999	2000
Paranal	—	15.8(5.7)	16.2(6.3)	15.0(7.3)	20.0(12.2)	16.4(7.6)	21.1(12.2)	25.5(14.4)
CAMC	21.0(14.1)	16.7(11.1)	26.5(10.8)	15.0(6.2)	15.6(15.0)	6.5(5.1)	19.7(10.2)	24.3(13.6)
Year	2001	2002	2003	2004	2005	2006	Average	
Paranal	22.8(15.4)	19.8(11.1)	15.3(8.2)	17.0(8.6)	18.0(6.0)	—	17.4 ± 3.4	
CAMC	21.9(9.1)	22.0(15.5)	24.5(3.6)	32.2(9.8)	—	—	27.0 ± 10.3	

**Table 8.** Paranal and CAMC: annual number of nights in which *RH* has been higher than 80% and 85% for more than 50% of the duration of the night. Only nights which duration has been  $\geq 6$  hours have been used in the calculation. For each year, the total number of nights having duration  $\geq 6$  is also reported.

Year	<i>RH</i> > 80%		<i>RH</i> > 85%		Nights	
	Paranal	CAMC	Paranal	CAMC	Paranal	CAMC
1984	—	2	—	2	—	155
1985	1	8	0	8	324	253
1986	0	8	0	8	311	285
1987	0	22	0	22	108	332
1988	0	51	0	51	258	349
1989	1	68	0	68	310	362
1990	0	73	0	73	329	354
1991	0	53	0	53	177	358
1992	—	58	—	58	—	366
1993	0	58	0	58	300	363
1994	0	41	0	41	328	355
1995	0	51	0	51	333	355
1996	0	81	0	81	348	354
1997	2	52	0	52	336	364
1998	0	36	0	36	348	359
1999	2	48	2	48	360	354
2000	4	49	2	49	365	333
2001	0	60	0	60	364	353
2002	4	31	3	31	362	274
2003	0	27	0	27	352	346
2004	0	35	0	35	365	334
2005	3	—	3	—	233	—

peratures, and an accelerator for the decrease. Conversely, a negative NAO Index acts in the opposite manner (see Paper I, Section 4).

In the case of Paranal we have analysed the Southern Oscil-

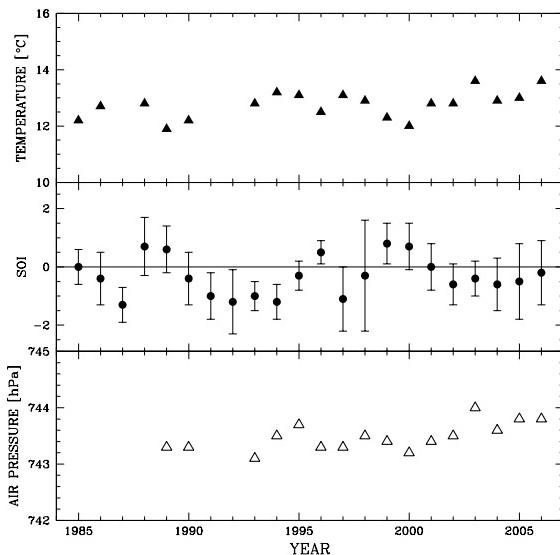
**Table 9.** Strongest El Niño and La Niña episodes between 1985 and 2006.

El Niño	La Niña
1987	1988
1992-1994	1996
1997	1999-2000

lation Index (SOI). The SOI is defined as the difference in air pressure occurring between the western and eastern tropical Pacific (Tahiti and Darwin, Australia). Changes in the SOI correspond also with changes in temperatures across the eastern tropical Pacific. The negative phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin (Halpert & Ropelewski(**author?**) 1992). Prolonged periods of negative SOI values reflect abnormally warm ocean waters across the eastern tropical Pacific, typical of El Niño episodes, while periods of positive SOI values coincide with abnormally cold ocean waters across the eastern tropical Pacific, typical of La Niña episodes<sup>4</sup> (Higgins et al. (**author?**) 2001).

Because of the strong influence of the SOI on the meteorological conditions in the southern hemisphere, and on observing conditions at Paranal and La Silla, it is important to investigate possible correlations between the SOI and the temperature and pressure at Paranal. For this reason we calculated the annual averages of the SOI from the monthly averages retrieved from the National Prediction Center Web

<sup>4</sup> See <http://www.cpc.ncep.noaa.gov>.



**Figure 8.** Southern Oscillation Index (*middle*) vs. annual temperatures (*top*) and annual air pressure (*bottom*) at Paranal. The error-bars in the *middle* plot correspond to the rms of the SOI annual means.

site.

Figure 8 (*middle*) shows the SOI as a function of the year where the error bars correspond to the rms of the SOI annual means. Each minimum in the figure corresponds to warm episode (El Niño), while each maximum to cold episode (La Niña). As shown in the figure and also reported in Table 9, strong El Niño occurred in the years 1987, 1992–1994 and 1997, while strong La Niña occurred in 1988, 1996 and 1999–2000.

The *top* of Figure 8 shows the  $T$  annual averages at Paranal. We see an increase in the annual temperatures in connection with El Niño, vice versa minimum temperatures occur with La Niña episodes (correlation is  $\sim 0.7$ ). Local minimum in the  $P$  annual trends at Paranal (Figure 8, *bottom*) are linked to the presence of La Niña events, while maximum with El Niño, but in this case poor correlations is found between the yearly trends at Paranal.

#### 4 ANALYSIS OF THE DEW POINT

The dew point temperature ( $T_{DP}$ ) is the critical temperature at which condensation occurs. When dew point temperature and air temperature  $T$  are equal the air said to be saturated and condensation appears if the air cools. It is clear that the knowledge of the dew point temperature is crucial for the maintenance of the optics of the telescope to avoid condensation, in particular if the instrumentation is maintained at temperatures few degrees lower than the air temperature. Condensation can be reached mostly in clear nights, when the earth cools rapidly, therefore it is important to know the percentage of time in which condensation may occur to have the best performances from ground based telescopes. To this aim we have computed the dew point temperature using nighttime data for both Paranal and CAMC. We have defined as nighttime the range 20:00–6:00 hr Local

Time. Only clear nights have been taken into account. The declared percentage of clear nights at ORM is 84% (Muñoz-Tuñón et al.(author?) 2007), while at Paranal it is 85% (<http://www.eso.org>).

The analysis concerns the annual percentage of time in which  $\Delta T = T - T_{DP} < X$ , where  $X$  corresponds to a variable upper limit for  $\Delta T$  ( $X = 1$  and  $5^{\circ}\text{C}$ ). This statistics is crucial for the knowledge of the amount of time in which a danger of condensation on the telescopes hardware may occur in two extreme  $\Delta T$ .

In Figure 9 we report the computed frequencies in the two sites. In winter, spring and autumn we see a significant difference between Paranal and CAMC until 2000. After such year the two sites seem to became more similar.

Paranal shows negligible percentages for all  $X$  limits in spring, while it never goes above  $\sim 4\%$  for  $X = 5^{\circ}\text{C}$  in winter (2002) and autumn (2002 and 2004). CAMC has frequency often  $> 10\%$  when  $X = 5^{\circ}\text{C}$ . After 2001 CAMC shows similar percentages with respect to Paranal when  $X = 1^{\circ}\text{C}$ . This is due to the very little increasing of the percentages at Paranal after 2001.

In summer the two sites are very similar maintaining percentages never higher than  $\sim 3\%$  at Paranal and  $\sim 4\%$  at CAMC when  $X = 5^{\circ}\text{C}$ , with the exception of the year 1990 for CAMC.

#### 5 ANALYSIS OF THE WIND

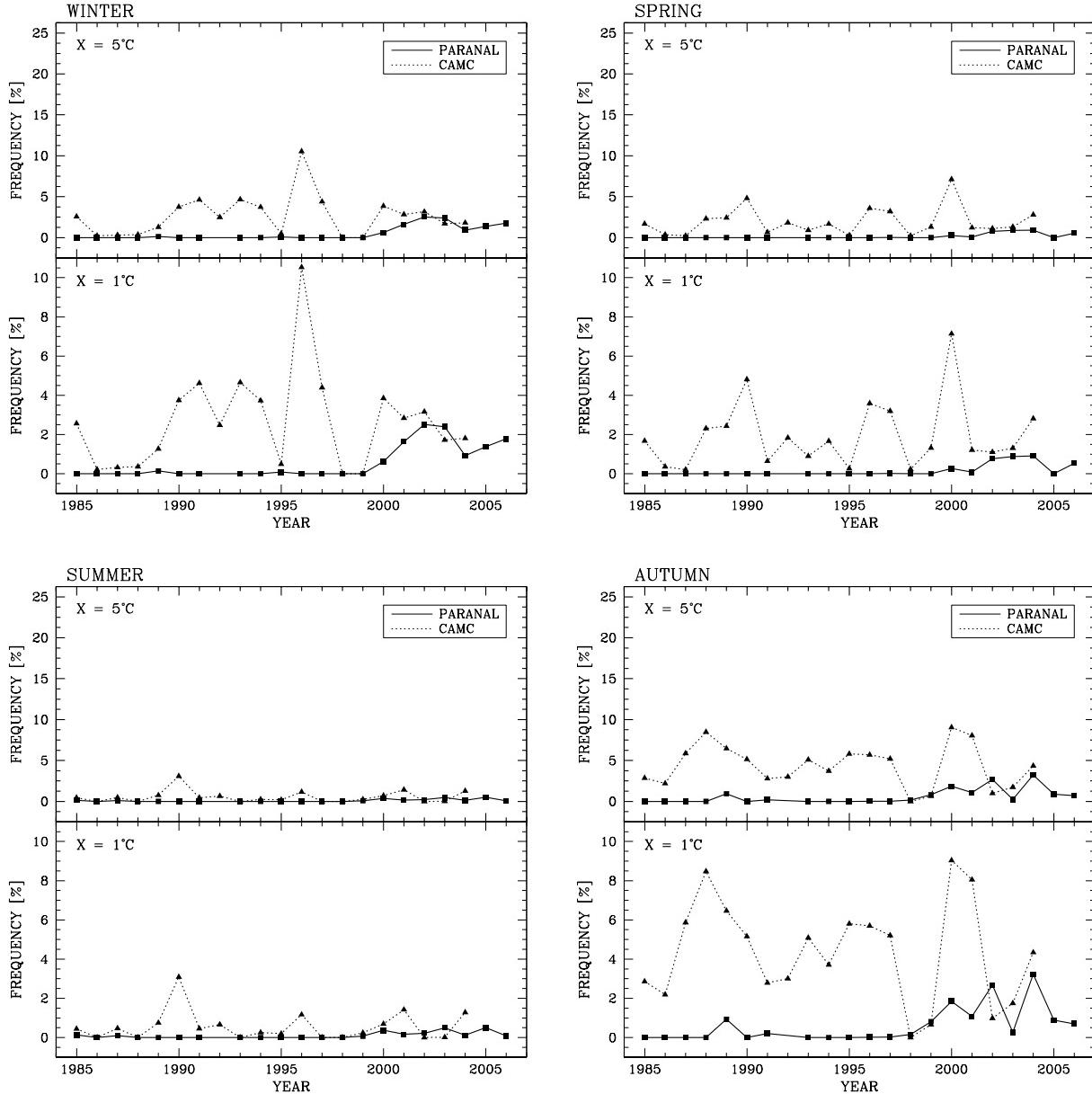
##### 5.1 Wind direction

In the analysis of the wind direction at Paranal we made use of a 9 years database between 1998 (VLT first light) and 2006. In Paper II the time range used in the computation of the wind statistics at CAMC was between 1998 and 2004. We consider only nighttime data, between 22:00 and 4:00 hr Local Time.

In Paper II we have demonstrated that there are significant differences in the wind direction and wind speed ranges among the ORM. In such paper we considered the locations of the CAMC, the Telescopio Nazionale Galileo (TNG) and the Nordic Optical Telescope (NOT). Because of the differences noticed in the three sites, none of them can be considered as fully representative of the ORM in wind analysis, so in this case we need to consider them together. In Figure 10 we show the wind roses computed for Paranal and CAMC, TNG and NOT (see also Paper II, Figure 2).

At CAMC there is no evidence of a prevailing direction. In Paper II we pointed out that northern winds seem to oscillate with a period of 10 years, while winds from the north-west show a similar oscillation in the opposite phase. TNG shows a dominant north-east mode, while NOT has two dominant wind directions (west and east).

Muñoz-Tuñón et al. (1998) demonstrated the homogeneity of the image quality among the ORM. Considering the difference between nighttime wind roses at different locations in the observatory that we have mentioned above, and considering also the complex orography of the ORM, should be interesting to investigate if any difference exists in the local Surface Layer seeing among the observatory. This is an important issue because local conditions have been demonstrated to be crucial for image quality at Paranal (Lombardi



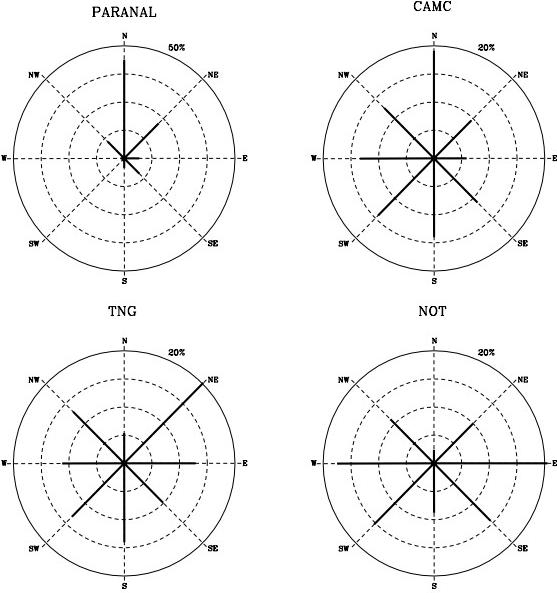
**Figure 9.** Nighttime annual percentage of time in which  $\Delta T = T - T_{DP} < 1$  and  $5^\circ\text{C}$  at Paranal and CAMC in winter, spring, summer and autumn.

et al.(author?) 2008b and Sarazin et al.(author?) 2008).

At Paranal a dominant wind blowing from north and north-east appears during the night. Table 10 reports the computed wind direction frequencies at Paranal between 1998 and 2006. The values in the table are plotted in Figures 11 and 12 where we include the wind frequencies since 1985 distinguishing two different epochs before and after the VLT first light occurred in 1998. Wind from north shows a clear decreasing trend through the years together with an increasing of the wind direction from south-east. This result is in agreement with Sarazin (2004) that in a previous analysis show a progressively replacement of the north-westerly wind by a north-easterly wind. To better investigate this behavior we have computed the yearly evolution of the nighttime frequencies of the wind in each direction. There is a strong

**Table 10.** Nighttime wind direction frequencies at Paranal from 1998 to 2006.

Year	N	NE	E	SE	S	SW	W	NW
1998	48.6	23.6	6.5	4.3	2.0	0.6	1.1	13.3
1999	46.7	23.3	6.2	8.0	3.7	0.4	1.2	10.5
2000	46.8	21.1	5.8	8.9	4.7	1.0	1.7	10.0
2001	45.8	19.6	7.8	9.8	3.4	1.1	2.0	10.5
2002	46.4	21.3	6.3	7.7	3.3	1.4	2.7	10.9
2003	38.5	19.8	7.2	14.6	4.0	1.9	2.0	12.0
2004	42.8	23.3	8.7	10.1	3.0	1.8	1.5	8.8
2005	38.6	19.3	5.6	12.3	8.0	3.4	1.1	11.7
2006	35.0	26.7	7.8	12.3	6.5	2.0	1.5	8.2
Tot.	43.8	22.0	6.8	9.6	4.2	1.4	1.7	10.5



**Figure 10.** Nighttime wind roses at Paranal (1998-2006), and CAMC, TNG and NOT (1998-2004).

**Table 11.** Nighttime yearly evolution of the wind direction frequencies at Paranal from 1998 to 2006 as [% per year].

N	NE	E	SE	S	SW	W	NW
-1.6	+0.3	+0.2	+0.9	+0.5	+0.3	< 0.1	-0.3

oscillation of the wind from north until 1994 (see Figure 11). Data from 1998 show a clear trend as shown in Table 11 that reports the computed trend of the yearly evolution of the frequencies in each direction. Wind from north is characterized by a decrease of the frequency of 1.6% per year marginally compensated by an increasing of wind coming from south-east (0.9% per year). We can conclude that progressively wind coming from the sea is replaced by wind coming from the Atacama Fault. At the moment it is not clear if we are in presence of a wide-scale changing of the atmospheric conditions or if this effect is induced by local conditions.

## 5.2 Wind speed

The analysis of the wind speed at Paranal and ORM is carried out from the calculation of the time in which  $w_{sp}$  is in fixed intervals established on the basis of the safety operations at the observatories. We consider five main situations:

- $w_{sp} < 3 \text{ m s}^{-1}$ : negligible wind speed, typically in this case the seeing increases (Paper II);
- $3 \leq w_{sp} < 12 \text{ m s}^{-1}$ : the wind speed is in the safety range, telescopes observe without restriction in the pointing direction, seeing conditions are optimal;
- $12 \leq w_{sp} < 15 \text{ m s}^{-1}$ : in this interval the telescopes can only point to objects in a direction  $\geq 90^\circ$  with respect to the actual  $w_{dir}$ );
- $w_{sp} > 15 \text{ m s}^{-1}$ : at ORM the telescopes are closed for strong wind;

**Table 12.** Nighttime wind speed statistics at Paranal (1998-2006) and CAMC, TNG and NOT (1998-2004).

$w_{sp}$ range [m s <sup>-1</sup> ]	Paranal [%]	CAMC [%]	TNG [%]	NOT [%]
$w_{sp} < 3$	22.1	83.6	30.2	18.5
$3 \leq w_{sp} < 12$	68.7	16.4	68.4	70.2
$12 \leq w_{sp} < 15$	5.9	0.0	1.1	7.1
$w_{sp} \geq 15$	3.3	0.0	0.3	4.2
$w_{sp} \geq 18$	< 0.5	0.0	0.0	1.2

- $w_{sp} > 18 \text{ m s}^{-1}$ : at Paranal the telescopes are closed for strong wind.

Table 12 reports the percentages of time in which the wind speed is in the fixed intervals. Also in this case, because of the wind speed differences noticed between CAMC, TNG and NOT, none of them can be considered as fully representative of the ORM, so they have to be taken into account together. For this reason Table 12 reports also the results for TNG and NOT obtained in Paper II.

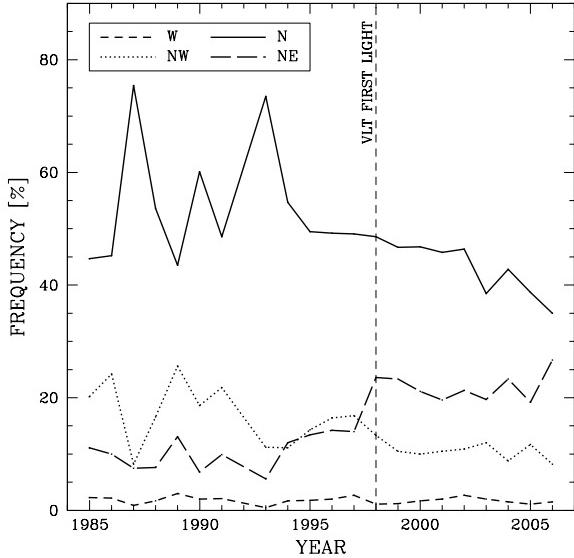
The site of CAMC has a predominance of  $w_{sp} < 3 \text{ m s}^{-1}$  (83.6%), while Paranal has 22.1%, TNG the 30.2% and NOT the 18.5%. Paranal preserves good wind speed conditions in the  $\sim 70\%$  of the time (same of TNG and NOT), while CAMC only the  $\sim 16\%$ . CAMC never shows  $w_{sp} > 12 \text{ m s}^{-1}$ , while Paranal has a percentage of 5.9 in the interval [12, 15] [m s<sup>-1</sup>] and 3.3% of  $w_{sp} > 15 \text{ m s}^{-1}$  while not-observing conditions due to strong wind occur in  $< 0.5\%$  of the time. The TNG has  $\sim 1\%$  of the time with  $w_{sp} > 12 \text{ m s}^{-1}$ , while NOT has considerable higher values in the intervals [12, 15] [ms<sup>-1</sup> s<sup>-1</sup>] (7.1%) and  $w_{sp} > 15 \text{ m s}^{-1}$  (4.2%). The highest wind speed measured at Paranal during the years 1998-2006 is 27.4 m s<sup>-1</sup> in May 2000.

## 6 CONCLUSIONS

We have compared the astroclimatological conditions at the Paranal Observatory and El Roque de Los Muchachos Observatory. Temperature, air pressure and relative humidity  $\sim 20$  years trends have been taken into account and significant differences resulted from the analysis. In particular, CAMC denotes a warming of  $\sim 1.0^\circ\text{C}/10\text{yr}$ , TNG data after 1998 show a flat trend, while the annual temperature trend at Paranal is characterized by a negative slope between 1993 and 2000 ( $-0.12$ ) while data in the period 2000-2006 have a positive slope (0.19). We have shown that using the pressure height scale both observatories are dominated by high pressure values and the computed pressure height scale at Paranal is 8334 m while at ORM it is 8325 m.

Typically in cold seasons  $RH$  is lower than 60% at CAMC and 15% at Paranal. In warm seasons  $RH$  is lower than 40% at CAMC and 20% at Paranal. A standard requirement for the use of telescopes is a  $RH$  value  $< 80\%$  or  $< 85\%$ . The number of nights in which  $RH$  has been higher than the mentioned limits for more than 50% of the duration of the night denote a significant difference between Paranal and CAMC, the first appearing almost immune to high  $RH$  events.

We have calculated the nighttime annual percentage of time in which the difference between the air temperature and the



**Figure 11.** Nighttime evolution of the wind direction through the years at Paranal (quadrant W-NE).

dew point temperature is lower with respect to a variable upper limit  $X$  ( $X = 1$  and  $5^\circ\text{C}$ ). The analysis has shown better conditions at Paranal with respect to CAMC in winter, autumn and spring until 2000, while the two sites are almost equivalent in the respective summer. Since 2001 the two sites are becoming more similar.

We have found a negative correlations between the Southern Oscillation Index and annual temperatures at Paranal (c.l. 0.7), while no correlation has been found between SOI and yearly air pressure in the same site.

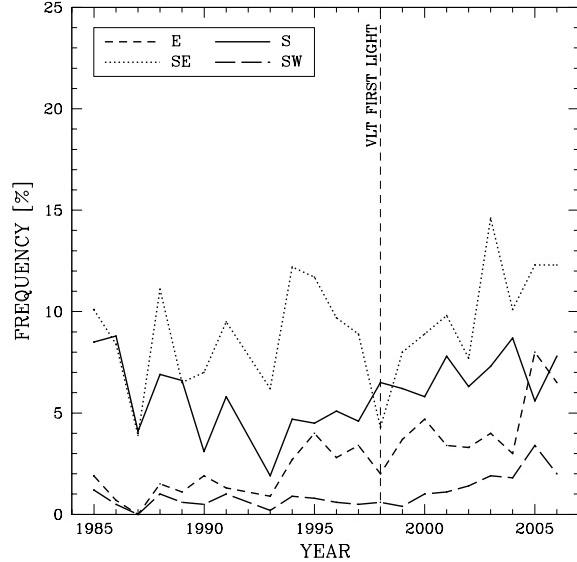
Paranal is typically dominated by wind from north and north-east in nighttime. The wind speed is lower than  $12 \text{ m s}^{-1}$  (safety range) in more than 80% of the time, while it is higher than  $18 \text{ m s}^{-1}$  less than the 0.5%. The mean wind speed is  $7.0 \text{ m s}^{-1}$  during the night. The same analysis at CAMC (see Paper II) shows that the mean wind speed is  $2.2 \text{ m s}^{-1}$ , but significant differences we found in both mean direction ad wind speed for each different telescope at ORM.

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**Figure 12.** Nighttime evolution of the wind direction through the years at Paranal (quadrant E-SW).

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